Journal of Environmental Science and Management SI-1: 49-58 (2025) ISSN 0119-1144

Greenhouse Gas (GHG) Emissions from Veneer Production from Falcata (*Falcataria moluccana* (Miq.) Barneby & J. W. Grimes) in the Caraga Region, Philippines

DOI: 10.47125/jesam/2025_sp1/05

ABSTRACT

The different processes involved in producing wood products are both sources and sinks of carbon, with CO_2e emitted from each operation. Greenhouse gas (GHG) inventory allows the measurement of net GHG emissions produced along each step of the process. This study was done to determine the GHG emissions resulting from falcata veneer production, specifically the processes from harvesting to veneer processing (drying). Falcata is a fast-growing commercial timber of high significance in the Caraga region in the Philippines. Updated emission factors were used to calculate the CO_2 e units. Major log transport contributed 49% of total emissions, resulting mainly from the use of trucks that is more than ten years old. The harvesting operation accounted for 21% of emissions while minor log transport involving carabaos, habal-habal (modified motorcycle) and small trucks (in various combinations) contributed to 18%. Veneer processing accounted for 12% of emissions because respondents used mostly air drying, hence, consumed less energy. Locating veneer mills close to existing plantations may reduce the GHG emissions significantly. Thus, the study sought to calculate the respective GHG emissions from harvesting, transport and veneer processing activities and determine the net GHG fluxes to and from the activities. These were accomplished through analysis of primary data gathered through direct observation and key informant interviews (KII). To describe the wood industry in the country in the context of climate mitigation, carbon stocks and emission rate from the wood production process using other tree species need to be quantified

Keywords: *greenhouse gas, GHG inventory, CO_2e, Veneer*

Diomedes A. Racelis[1*]
Dalisay Espiritu-Cabral[2]
Vanessa M. Palma-Torres[1]
Canesio D. Predo[1]
Elenita L. Racelis[1]
Wilfredo M. Carandang[1]

[1] College of Forestry and Natural Resources, University of the Philippines Los Baños, College, Laguna, Philippines 4031
[2] Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development-Department of Science and Technology, Philippines

*corresponding author: daracelis@up.edu.ph

INTRODUCTION

Forests can be a source or sink of carbon, depending on the balance between photosynthesis and respiration and the degree to which they are converted into other land uses (*Berg and Karjalainen 2003*). In photosynthesis, trees absorb carbon dioxide (CO_2) from the atmosphere and store carbon (C) in their biomass and soil (*Brown et al. 1996*). In relation to this, greenhouse gas (GHG) emissions are pivotal in driving climate change, particularly within the forestry sector. Deforestation and forest degradation contribute significantly to GHG emissions, as trees that once sequestered carbon are removed, releasing stored carbon dioxide back into the atmosphere. Additionally, forest utilization practices, such as logging and land conversion for agriculture, can further exacerbate emissions if not managed sustainably. The forestry sector's impact on climate change is not only due to emissions from land-use change but also from forest management practices that can either mitigate or enhance these emissions. Accurate measurement of GHG emissions in this sector is essential for developing effective climate policies and conservation strategies. By quantifying emissions, stakeholders can identify the most significant sources and implement targeted interventions. Furthermore, measuring GHG emissions allows for the monitoring of progress toward climate goals and commitments, such as those outlined in the Paris Agreement. Sustainable forest management and reforestation efforts can significantly reduce emissions while promoting biodiversity. Therefore, understanding the relationship between GHG emissions and forestry practices is crucial for addressing climate change. Continued research and investment in emission measurement technologies will be vital for informed decision-making in the sector.

Researches on the mitigation potential and environmental merits of High Density Wood Products (HWPs) have been conducted since the early 1990s, when investigators of the forest carbon budget started considering the effects of harvesting and utilizing wood products (*Winjum et al. 1998*). However, a thorough investigation of the fate of wood products has yet to be carried out. The limited data in this regard is due to the practical impossibility of tracing the trade path and life span of imported and local wood after the timber is harvested and sold. Other factors such as stocktaking and possible reuse of wood products at different stages of its life cycle further complicate the assessment (*Profft et al. 2009*). Thus, a product-by-product approach in HWP accounting is not straightforward and requires a lot of data mining and analysis.

Wood products are important for the analyses of the mitigation potential of the forestry sector in terms of climate change. Although they can contribute to carbon dioxide (CO_2) and methane (CH_4) emissions in the atmosphere when they are burned or decay in harvesting sites and landfills, wood products can also act as a carbon sink during their service life and require less energy in their production compared to other materials (*Dias et al. 2007*). A factor unique to forest products is the sequestration and storage of carbon by trees in their woody biomass.

The harvesting of trees and their processing into various wood products ultimately produce emissions. In particular, the use of fossil fuel and of other sources during harvesting, log transport, and veneer processing operations emit a considerable amount GHG that could be traced through inventory and attempts could be made to minimize these emissions. The GHG inventory begins with the harvesting operation and ends with the drying of veneer products. Two parallel and related streams of GHG impacts result directly from the harvesting, transport, and processing. First, the use of fossil fuel, wastes generated during the operations, and electricity consumption in producing the product emit CO_2, CH_4, N_2O, and other gases. Second, carbon is stored in the end product (veneer) for a long time.

Utilizing forest carbon analysis together with life cycle analysis (LCA) tools could provide a more comprehensive evaluation of GHG emissions associated with structural forest products (*Perez-Garcia et al. 2005*). This indicator allows the numerical assessment of the amount of GHG emissions produced as a result of a process, product, event or service, and is expressed as mass of CO_2 equivalent (CO_2e). A carbon footprint shows environmental impact through emissions associated with different GHG inventories, and its calculation is a first step toward engagement and corporate environmental responsibility.

Adhikari and Ozarska (*2018*) conducted a meta-analysis to examine methods for reducing the environmental impacts associated with timber products, spanning the process from sawmills to finished goods. Key goals include identifying the main sources and mechanisms behind these impacts, evaluating current energy use and greenhouse gas emissions in timber processing and manufacturing, and exploring strategies to mitigate them. Environmental challenges are evident throughout the entire wood supply chain. Numerous studies-especially those using Life Cycle Assessment (LCA) methods- have offered in-depth insights into energy use, manufacturing processes, and their environmental consequences. Potential solutions include shifting energy consumption habits, adopting renewable energy, enhancing sawing and drying techniques, managing wood waste more effectively, and using less harmful chemicals. In addition, strong policy support and active collaboration among stakeholders are essential to promote integrated industrial operations, improve product quality, and advance environmental sustainability as part of a broader sustainable development framework for the timber sector.

Chen et al. (*2018*) developed a life-cycle analysis (LCA) framework to evaluate carbon dynamics associated with Canadian-produced harvested wood products (HWP). The analysis considered carbon storage in HWP both in use and in landfills, emissions offset by substituting HWP for non-wood construction materials, emissions from HWP production, and methane emissions from wood decomposition in landfills. Five different HWP production scenarios were analyzed, with structural panels showing the greatest potential for greenhouse gas (GHG) mitigation, followed by lumber and non-structural panels. The net GHG impact of Canadian HWP was assessed by integrating these carbon dynamics with forest carbon modeling across four forest management units in Ontario, covering 2.21 M ha of timber-managed forest. Based on average displacement factors, the time required to achieve net emission reductions varies by product type- ranging from immediate for structural panels to up to 84 years for business-as-usual production- yielding net reductions between 21 and 112 Mt CO_2-equivalent over a century. These findings highlight that producing long-lived HWP from sustainably managed Canadian forests can play a significant role in climate change mitigation.

Liangliang et al. (*2019*) employed Life Cycle Assessment (LCA) to identify the environmental impacts and key hotspots in plywood manufacturing in China. The assessment followed a cradle-to-gate approach, covering stages from raw material preparation to plywood processing, and focused on key impact categories including abiotic depletion (ADP), acidification (AP), primary energy depletion (PED), freshwater eutrophication (EP), global warming potential

(GWP), and particulate matter formation (RI). Data were sourced from on-site production measurements and upstream databases like Eco-invent and CLCD, with minor environmental contributions and low-quantity auxiliary materials excluded based on predefined thresholds. To reduce environmental impacts, the study recommended an eco-design strategy that includes using pyrolysis bio-oil for green resin as a substitute for traditional phenolic formaldehyde (PF) resin, and implementing green gluing technologies along with gasification of wood waste instead of combustion. Additionally, plywood was compared to other wood-based panels produced in China to identify further opportunities for improving sustainability.

Pommier et al. (*2016*) applied Life Cycle Assessment (LCA) to evaluate the environmental viability of this vacuum process using green veneers. It compares different adhesives, bonding techniques (vacuum vs. traditional), and wood types, analyzing four conventional plywood products against the new one- all meeting *EN 13986* (*2004*) quality standards. LCA modeling, aligned with ISO 14040 guidelines, indicates strong environmental advantages for vacuum gluing green wood, though the use of consumables remains a drawback that could be minimized in scaled-up production with reusable materials.

This study attempts to quantify the GHG emissions and fluxes of producing veneer products in the Caraga Region in the Philippines.

MATERIALS AND METHODS

This research was part of the one-year project on "Greenhouse Gas (GHG) Inventory of Industrial Tree Plantation (ITP) Production Chain in CARAGA Region, Mindanao" conducted between July 2018 and June 2019. Falcata [*Falcataria moluccana* (Miq.) Barneby & J. W. Grimes] was chosen as the species to be studied since it is the main wood species used in the veneer, plywood, and lumber production of the wood industry in the Caraga Region. It also has the largest plantations, timber production volume, and commercial value in the region.

The study involved four types of GHG inventory from selected falcata plantations in the region, namely:GHG emissions inventory during harvesting operations (e.g., felling, bucking; minor and major log transport from stump site to the processing plant; inventory of GHG emissions from primary wood processing into veneer; and C emission inventory from logging residuals left to decay and milling wastes. These types of inventories were further subdivided by scope based on the IPCC guidelines. The GHG emissions were categorized by sources into three scopes (*WBCSD/WRI 2004*) for which separate calculations were made as well: Scope 1- direct emissions (i.e., fuel emissions); Scope 2- indirect emissions (i.e., purchased electricity); and Scope 3- indirect emissions (i.e., wastes from harvesting and primary wood processing operations).

The researchers then set the system boundary of the study with the prior mentioned types of GHG inventory within the life cycle of Falcata veneers (**Figure 1**).

The system boundary defines the unit processes to be included in the system. The unit systems included inputs and outputs in the main processing sequence, transportation, production and use of fuels, electricity and wastes generated.The flow of the wood material was analyzed in each operation and generated wastes separately quantified. The process conversions were examined and the resulting wood product volume was calculated.

Rihm et al. (*2024*) calculated the carbon stock changes in the HWP pool by applying the so-called production approach for three semi-finished wood product categories: sawnwood, wood-based panels and paper and paperboard. Activity data were collected from international database (FAOSTAT) as well as from surveying the Swiss wood industry (Tier 2 and 3 methodologies). For calculating carbon stock changes in HWP, Switzerland applied the default first order decay model using the corresponding default half-lives (35 years for sawnwood, 25 years for wood panels and 2 years for paper and paperboard; Tier 2 methodology). HWP originating from imported wood were excluded from the accounting and HWP originating from deforestation activities were accounted for on the basis of instantaneous oxidation. 1/14 Harvested wood products (HWP) in the Swiss Greenhouse Gas Inventory – NID 2024 Reference: R113-0811 The total inflow of carbon to the HWP pool in 2022 amounted to 408 kt C (60 % from sawnwood, 35 % from wood panels, 5 % paper and paperboard). The outflow from the pool was reported to amount to 399 kt C in 2022 (57 % from sawnwood, 34 % from wood panels, 9 % paper and paperboard). Thus, there was a net carbon gain in HWP of around 10 kt C or -36 kt CO_2 in 2022.

Data Collection

Both primary and secondary data were utilized in this study. Personal interviews were conducted among farmers, truckers, and sawmill operators using structured survey questionnaires to capture all quantitative and qualitative information needed. The Slovin's Formula was employed

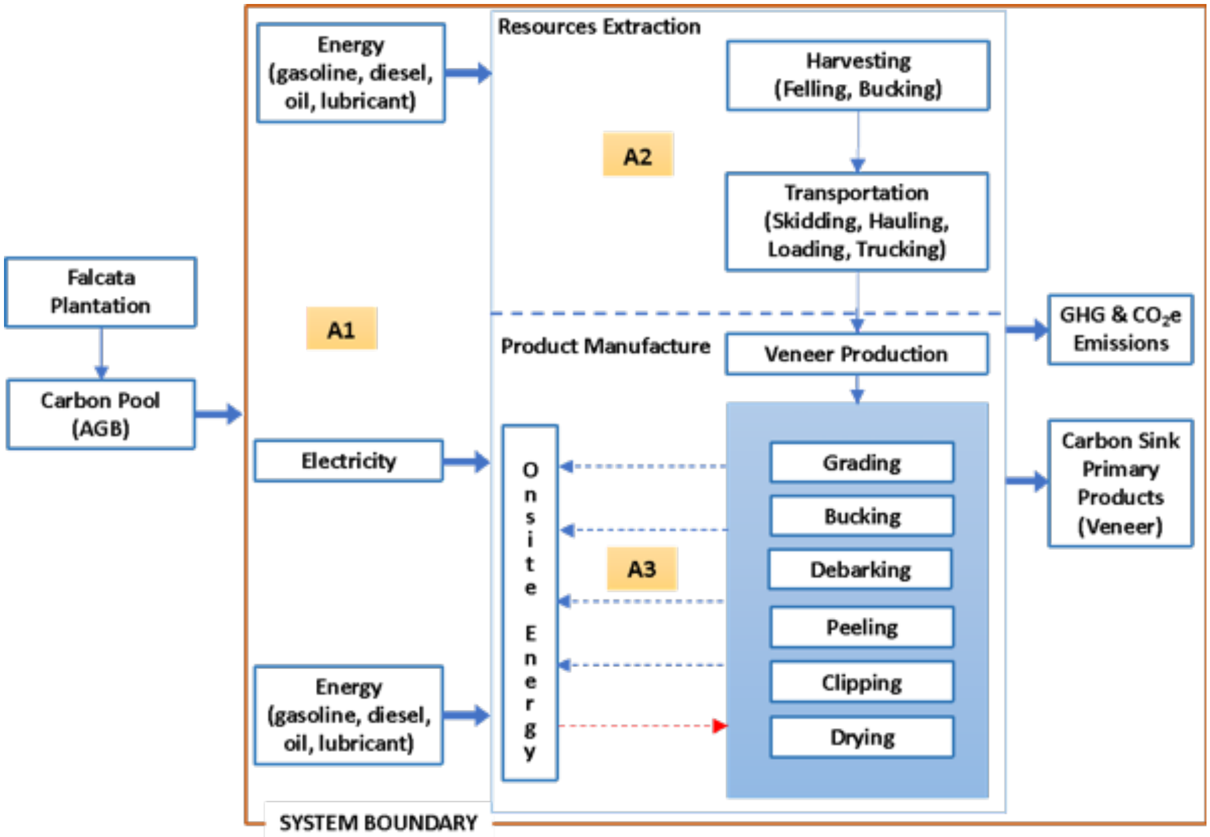

Figure 1. Operational boundary of veneer manufacture (falcata). (Diagram drawn and modified based from *Bergman and Alanya-Rosenbaum 2017*).

to obtain the number of respondents for each of the above mentioned set of actors that represents the ten Community Environment and Natural Resources Offices (CENRO) of the Department of Environment and Natural Resources (DENR) in the Caraga Region (Nasipit, Cabadbaran, Bayugan, Bunawan, Loreto, Talacogon, Surigao City, Cantilan, Bislig, and Lianga).

To determine the sample size of the farmer-respondents, the Slovin's Formula was used as follows:

$$n = \frac{N}{1 + Ne^2}$$

Where: n is the sample size
N is the population size
e is the desired margin of error

In this study, N is the number of tree farmers engaged in falcata tree plantations. Five percent error was used as referenece in calculating the sample size with 95% level of confidence. Based on the list from the 10 DENR CENROs of DENR Region 13, a total of 616 registered tree farmers were engaged in harvesting operations in the region.

For the respondents involved in major log transport and wood processing, data was collected following a stratified random sampling approach. Those who were engaged in transporting falcata logs from January to September 2018 were considered both for minor and major log transport operations.

Wood processing plants (WPPs) sampled were stratified into sawmill type and within each sawmill type or strata, sampling for fuel used and electricity consumed during the operation from log grading to drying was randomly done at 30 replicates per sawmill type.

To validate the findings from the surveys, key informant interviews (KIIs) were done with the representatives from various stakeholder groups, including leaders of plantation tree farmers' associations, municipal and provincial government, and non-government organizations (NGOs) involved in wood harvesting, major log transport and wood processing plants and those who are knowledgeable on the wood industry operations. Focus was on the volume harvested and method of disposal during the harvesting operation, fuel used during the minor and major log transport and the fuel and electricity consumed for processing the logs to lumber and veneer. Drying of primary products was also considered for the WPPs with drying facilities.

The data collection began with discussions with the respondent farmers engaged in harvesting and/or minor and major log transport operations about the area and volume harvested and other information that describes the area and operations. A set of questionnaires was used for the four operations. For the sawmill facilities, energy usage and operating characteristics of the manufacturing equipment was discussed with plant operation engineers. Major energy-consuming equipment were identified based on its rated capacity.

In addition, information related to the sources of logs, costs incurred in the operations, and methods for waste disposal along the processes were obtained. All the data were assumed to be on an annual basis since they covered the operations from January to September 2018 when most of the activities were done per process. Based on the interview, the operation (if any) for the last quarter of the year (October to December) was not significant as it entailed fewer activities due to weather conditions, demand, and prevailing prices for veneer and lumber products.

Observations were also conducted on selected Falcata farms and Wood Processing Plants (WPPs) to document the activities and practices at each stage of veneer production and to account for all the costs, energy and fuel consumption, and product volume production within the designated system boundary (**Table 1**).

Secondary data, such as default value for biomass of falcata, were collected and other completed studies were analyzed. The list of Industrial Tree Plantations (ITPs) with 5-to-8-year rotation ages was obtained from the private tree plantation ownership certificate (PTPOC) submitted to the Department of Environment and Natural Resources (DENR). A list of registered wood processing plants (WPPs) in 2018 was also obtained from the same government office. Harvesting activities, major transport and wood processing of logs to veneer were generated based on the operations conducted between January and September in 2018.

Table 1. Type of data collected from the survey.

Process	Inventory Data
Felling process	Average age of the log, Type of machine used to harvest, Working hours, Type of fuel and fuel consumption
Minor Log Transport	Mode of transportation, Type of fuel and fuel consumption, Mileage, Carabao manure during hauling operation
Major Log Transport	Mode of transportation, Type of fuel and fuel consumption, Mileage, Age of truck used
Sawmill	Type of machines used, Working hours of the machines, Type of fuel and fuel consumption, Volume of veneer product, Electricity consumption

GHG emission calculation

The GHG inventory covers all steps of the veneer production process, beginning with fuel consumption during harvesting operation, followed by hauling from the stump site to roadside using carabaos and either habal-habal (modified motorcycle) and/or small truck, transporting the logs from roadside to sawmill using 10-wheeler trucks, and the actual veneer production. The GHG contribution from carabao manure during hauling was also considered.

During the veneer processing, fuel used for bucking and loading was measured as well as the electricity consumption per equipment used throughout the process. These processes consume electricity drawn from the national grid through AGUS VI Hydroelectric Power Plant (HEP) and distributed by electric cooperatives within the Caraga Region. The fossil fuel consumed as the biomass generated along the process was also considered in the inventory.

The inventory was done ananalyzed following the basic principles of *IPCC* (*2006*) and *EMB* (*2011*) inventory manual for tracking GHGs. The global warming potential (GWP) was calculated using the values of *IPCC Fifth Assessment Report* (*2014*). Wood density of falcata (280 kg m^{-3}) (*Romano and Acda 2017*) was used to calculate the emissions from mill wastes and wastes left to decay.

CO_2 emission factors and other default values were sourced from the *Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories* (*2006*), the *International Energy Agency* (*2010*) and the *EMB Tracking Manual for GHG Inventory* (*2011*). Updated emission factors were used to calculate the CO_2 eq units (**Table 2**).

Table 2. Global Warming Potential (GWP).

Greenhouse Gas	Chemical Formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265
Hydrofluorocarbons	HFCs	4-12,400
Perfluorocarbons	PFCs	6,630-11,100
Sulphur hexafluoride	SF_6	23,500

Source: *IPCC 2006*

Methane and nitrous oxide emission factors for grid electricity were derived from the national grid, International Energy Agency, and *IPCC* (*2006*).

The potential GHG sources and sinks were considered in determining the net amount of GHG released or captured. The carbon stored from harvested wood (biomass), and emissions of GHGs were quantified from harvesting, transport and sawmilling operations through vehicles used, electricity consumption, and wastes produced during the implementation of activities/ processes. Wood density of falcata and default values from *IPCC* (*2006*) and *EMB* (*2011*) for emission factors, carbon content, and expansion value among others were used. Detailed and relevant data on each stage (harvesting, transport and sawmilling operations) were collected through in-depth interviews with farmers, transport groups, and veneer mills operators.

Through the use of a spreadsheet, the equations used in calculating the GHG emissions from harvesting, transporting and wood processing operations were documented. Wood density and default values on emission factors, conversion values and other information related to GHG taken from literature were also included in the input data. The spreadsheet includes calculation of Scopes 1 (Direct Emissions), Scope 2 (Emissions from Electricity) and Scope 3 (Other Sources of Emissions).

The net GHG fluxes for the entire production chain of falcata plantation were computed to assess how much CO_2 is absorbed or released during the process and whether the net is positive or negative. Positive net CO_2 fluxes mean that the ITP operation is more of a carbon absorber while negative net flows connote that the project is a carbon emitter.

The study computed the CO_2 net emissions or uptake value based on the total CO_2 stored per volume of veneer produced out of the total volume of logs as input variable for wood processing operation. The following generalized equations were used to calculate GHG emissions for each identified emission source and the net GHG Fluxes (*Environment Management Bureau 2011*).

$$\text{Total } CO_2e \text{ Emissions} = \sum (\text{Activity data x } CO_2 \text{ emission factor x } 1) + (\text{Activity data x } CH_4 \text{ emission factor x } 28) + (\text{Activity data x } N_2O \text{ x } 265) \quad (1)$$

$$\text{Net GHG Fluxes} = CO_2e \text{ Stock from veneer product} - CO_2e \text{ footprints from operations} \quad (2)$$

The carbon stored in the product at the manufacturing stage and the identified wood density for falcata (280 kg m^{-3}) served as the basis for the analysis. The carbon stored may then be considered against the emission from operation to come up with the net GHG fluxes for veneer production.

A similar study was conducted by *Lao and Chang* (*2023*), which quantified the GHG footprint of wood-based panels (WBPs) produced in China. They used cradle-to-gate life cycle models developed for plywood (PLY), fiberboard (FB), particle board (PB) and oriented strand board (OSB) in the study. Results showed that the GHG footprints of PLY, FB, PB and OSB without considering biogenic carbon storage are 538 kg CO_2e m^{-3}, 406 kg CO_2 e m^{-3}, 348 kg CO2e m^{-3} and 552 kg CO_2 e m^{-3}, respectively. For the four types of WBPs, resource extraction stage provides the largest contribution to the GHG footprints (55%–81%), followed by the production process (18%–31%) and raw material transportation (1%–18%).

RESULTS AND DISCUSSIONS

Fuel consumption (Scope 1)

Under the Scope 1 (*WBCSD/WRI 2004*), the fuel for the processes of harvesting falcata logs within the system included gasoline, diesel, oil, and lubricant (**Table 3**).

Key informants (KI) mentioned that the efficiency of the equipment and vehicle used during the operation was based on the age of the specific equipment/vehicle and whether it was regularly maintained. For instance, a new chainsaw (<5 years) can produce 6 m^3 of logs L^{-1} of gasoline while an older unit (>5 years) could produce only 2 m^3 logs per liter. Similarly, for major log transport, the new vehicle (<10 years old) was more efficient (8 km L^{-1} of diesel) than the old one (>10 years old) (2.6 km L^{-1} of diesel).

Gasoline and oil were the main fossil fuels consumed during minor log transport while diesel and oil were mainly used for the major log transport. The average travelling distance was 3.47 km for habal-habal, 9.67 km for small truck, 1.31 km for carabao and 0.79 km for manual hauling. For major log transport (roadside to sawmill), the average distance was 160.24 km.

Among the operations/activities studied, the wood processing stage uses the most fuel (43.91%), with veneer production using up 37.16% of this volume. This could be due to the larger diameter of the logs used

Table 3. Average fuel consumption of harvested logs (L m^{-3}) (computed).

Process/Source	Gasoline	Diesel	Oil	Lubricant	Total
Harvesting					
Chainsaw	0.608	-	0.059	0.104	0.771
Minor Log Transport					
Habal-habal	0.699	-	0.014	-	0.713
(Small truck)	0.411		0.005		0.416
Major Log Transport					
10-wheeler truck	-	1.456	0.056	-	1.512
Wood Processing					
Veneer production	0.920	1.144	0.009	0.188	2.261

for veneer production requiring more gasoline for the bucking operation in the sawmill.

Major and minor log transport were almost similar in fuel consumption, with major log transport using at least 6% more fuel. Expectedly, harvesting had the least fuel consumption with the chainsaw consuming less than one L m^{-3} of logs.

Among the different fuels, gasoline had the highest consumption volume (3.024 L m^{-3}), accounting for nearly half of the total fuel used in all operations except for major log transport, where diesel powers the 10-wheeler trucks. Diesel was the second fuel most consumed in volume, although it was used only in the latter stage of the wood industry operations from major log transport to wood processing.

The lubricant is used in all stages of the operations, but because it was used in small amounts, it added up only to 5% of the total fuel consumption. Oil was the least consumed, making up only 2.42% of total fuel consumption, about 0.147 L.

Energy consumption (Scope 2)

The typical sources of energy utilized in wood processing plants are electricity, natural gas, wood waste, and fuel oil. For veneering plants, electricity is required for equipment operations such as debarking, peeling, clipping, and drying. Electricity is required to operate motors in equipment for lumber veneer mills such as debarker, trimmer, ripsaw, kiln dryer, and material handling equipment (i.e., conveyors and belts). Normally, wood waste is used in the boiler (steam generator) to generate low-pressure steam used to dry veneer.

Data showed an average annual electricity consumption of 30.58 kWhr for an estimated 72,182.86 m^3 of veneers produced in the Region. The ratio of the annual electrical energy consumption in kilowatt hour (kWhr) to the production rate was 6.2%. This was due to the use of wood wastes as boiler fuel during the operation.

Wastes generated (Scope 3)

Wastes from logging residuals left to decay, milling wastes, and carabao manure during minor log transport were also accounted for. An average of 0.05 m^3 was left to decay in the stump sites while about 0.45 m^3 wastes was generated during veneer production. The 0.45 m^3 waste was then used as fuel for steam dryers. Both practices emitted a total of about 0.030 Mg CO_2e m^{-3} and 0.008 Mg CO^2e m^{-3}, respectively, while wastes from carabao manure generated about 0.075 Mg CO_2e m^{-3}. Higher emissions came from minor log transport due to carabao manure that produces more methane and nitrous oxide compared to carbon dioxide.

GHG Emission per Source of Operation

Within the veneer production system boundary, logs removed from the harvested sites represented approximately 60% of the total volume of stored carbon, 10% was taken as fuel, 5% as wastes left to decay at the harvesting site, and 25% ended up at the veneer processing stage. Almost half of the CO_2e emissions (49%) came from major log transport, while half of this value came from harvesting (**Table 4**). The least volume of emissions is attributed to veneer processing. This may be due to the relative newness of the sawmill equipment used, as well as air drying in lieu of the conventional

Table 4. Carbon emissions from the various production steps for falcata veneer.

Production step	Emission (Mg CO_2e m^{-3})	Proportion
Harvesting	0.089	21
Minor Log Transport	0.077	18
Major Log Transport	0.215	49
Veneer Production	0.054	12
TOTAL	0.435	100

furnace drying for most of the sampled WPPs.

The results are comparable to the study made by *Kühmaier, et al.* (*2022*) which analyzed the greenhouse gas (GHG) emissions caused by the forest supply chain in Austria using Life Cycle Assessment (LCA) methods. In the study, the forest supply chain consisted of several processes like site preparation and tending, harvesting, and transport. In total, 30 relevant forest processes from seedling production until delivery of wood to the plant gate were considered. In 2018, a total of 492,096 t of CO_2e were emitted in Austria for harvesting and transportation of 19.2 m^3 of timber. This corresponded to 25.63 kg CO_2e m^{-3}. At 77%, transport accounts for the largest share of emissions within the supply chain. Extraction causes 14% of emissions, felling and processing cause 5%, and chipping causes 4%. GHG emissions for felling, delimbing, and crosscutting are much lower when using a chainsaw compared to harvester. The high numbers for the transport can be explained by the high transportation distances. Especially for the transportation of wood, it is necessary to find more climate-friendly solutions from a technical and organizational point of view. The provision of wood is climate-friendly, and its use enables the substitution of fossil fuels or materials with higher negative effects on climate change such as aluminum, steel, or concrete.

Prakash et al. (*2025*) conducted a gate-to-gate life cycle assessment (LCA) for 1 cubic meter of finished plywood (600 kg/m³) from four different manufacturing facilities, varying by location, capacity, and product types. Primary data on inputs and outputs were collected through staff interactions and used to simulate the manufacturing process in GaBi, with secondary data from its 2011 database. The study analyzed energy demand, greenhouse gas emissions, and other pollutants, with a breakdown of biogenic and fossil CO_2 emissions, as well as sequestered carbon. Electrical energy was mainly used in veneer peeling, drying, and hot pressing, with veneer drying identified as the most thermal energy-intensive process. Material recovery ranged across factories due to factors like log quality and operator skill, with the best recovery rate at 63%, suggesting room for improvement. Overall, plywood was found to store more carbon than it emits during production, making it a sustainable alternative to materials like steel and aluminum.

Tajana et al. (*2024*) analyzed the Cumulative Energy Demand (CED) of decorative wooden wall coverings made from veneer to assess their environmental impact during material extraction and production. Using SimPro software in compliance with ISO 14040 and 14044 standards, the analysis identified key energy-intensive processes and materials through a characterization chart for 1 kg of veneer product. A Network chart further highlighted environmental hotspots in the veneer production process, offering valuable insights for improving sustainability. The data gathered can support early-stage product design decisions and help optimize manufacturing for greater energy efficiency. Overall, the study confirms CED as a useful tool for pinpointing areas for energy reduction and guiding more sustainable practices in the veneer and wood product industry.

Total and Net GHG fluxes

The amount and type of energy used has a substantial impact on the holistic environmental impacts of veneer production. The study showed that 0.197 Mg CO_2e was released in the production of 1 m^3 of veneer. Carbon content for wood products is assumed to be 44% of the wood density (*UNFCC 2003*), equivalent to 0.462 Mg CO_2 m^{-3} emissions if left to decay. This resulted in a net GHG influx of 0.266 Mg CO_2 m^{-3}.

The results corroborate the study of *Kayo et al.* (*2015*) which developed a model to evaluate the overall climate change mitigation potential of harvested wood products (HWPs) in Japan, incorporating carbon storage, material substitution, and energy substitution effects. The model projects impacts through 2050, based on future scenarios for domestic forestry, HWP utilization, and energy use. Under the production approach, the maximum carbon storage effect from HWPs is projected to reach 2.9 MtC per year by 2030, with the same figure projected for material substitution by 2050. The energy substitution effect could peak at 4.3 MtC per year by 2050, with over half of this impact coming from regions in eastern and western Japan due to abundant logging residues. Combined, the maximum climate change mitigation effect from HWPs could reach 8.4 MtC annually by 2050-about 2.4% of Japan's current CO_2 emissions. The study concludes that continued promotion of domestic wood production and increased HWP use will yield steady mitigation benefits, particularly through substituting non-wood buildings with wooden ones and expanding the use of logging residues for energy.

CONCLUSIONS AND RECOMMENDATIONS

The study sought to determine the GHG emissions of veneer production using direct observation and key informant interviews (KII). It demonstrated that the use of air drying and wastes for steam drying during veneer processing operation reduced the emissions significantly.

This shows that increasing the amount of time for drying the wood product in the open air significantly reduces electricity consumption and eventually reduces GHG emissions. The type and condition of the equipment used resorting to cleaner fuels could reduce the GHG emissions. Locating veneer mills close to existing plantations and fuel efficiency of vehicles used may reduce emissions from major log transport operations. As part of Research and Development (R&D), efforts should be exerted to find ways on how the wastes from wood processing firms can be utilized as an input in the production of new products. This could potentially reduce costs and promote the environment-friendly image of wood processing firms. Furthermore, the firms should be strictly monitored by the government in the management of their own wastes.

Wood processing plants (WPPs) must utilize sophisticated, efficient, and highly automated processes to ensure that the best features of a given wood resource are used to the best advantage to create the optimal product with minimal wastage. Residuals from the manufacturing process, such as bark, planer shavings, sander dust, sawdust, and trim should be either returned to the process, used as fuel to dry wood or produce steam for boiler, or made into other products.

For the overall CO_2e emission, the carbon stored in harvested wood products like veneer is clearly an important part of the industry's impact on the global carbon balance. The amount of carbon stored in veneer products is larger than the amount emitted by the industry's manufacturing facilities proving that veneer production is a net carbon sink rather than an emitter. Future work will enhance the model by incorporating the carbon footprint of the end-of-life emissions of veneer products in order to establish the full cradle-to-grave life cycle.

For future carbon footprint research, this study provides the base data for veneer production and presents a methodology which is also useful for other wood-based products. With a better understanding of the processes and components that are large energy consumers and emitters of GHG, improvements in efficiency to reduce energy use and GHG emissions can be better targeted for future research.

Future research should also include a full life cycle assessment of the wood production chain and a forest landscape carbon balance analysis to come up with the overall GHG emissions in the whole process.

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ACKNOWLEDGMENT

This article is part of the research project entitled "Greenhouse Gas (GHG) Inventory of Industrial Tree Plantation (ITP) Production Chain in Mindanao - Phase 2" funded by the Department of Science and Technology - Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (DOST-PCAARRD). The authors sincerely extend their profound gratitude to the funding agency for their support in this endeavor in providing strategic leadership to advancing scientific research in this field. The team also wish to thank all the persons who supported and participated in the study: Ms. Ma. Cecilia Marza (IRNR, UPLB-CFNR), For. Rustum A. Aguilos (FWRDEC, DENR-ERDB), For. Jorinells S. Hagos, For. Maria Kristina Abigail S. Lapitan and For. Lawrence Adolph M. Amada (FERD, DOST-PCAARRD).